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DEVELOPMENT AND VALIDATION OF EPH MATERIAL MODEL FOR ENGINEERED ROADWAY SOIL

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ABSTRACT

Full-vehicle, End-to-End under-body blast (UBB) simulations with LS-DYNA have been common practice at the Tank Automotive Research, Development and Engineering Center (TARDEC) for the last several years to support Program Managers in the Army Acquisition of military ground vehicles. Soil, which is one of the four key components (with air, charge, and vehicle structure being the others), has been represented in these simulations by an Elastic-Plastic Hydrodynamic (EPH) model. EPH models has been available for the currently used Double-Sifted (DS) Topsoil since 2012, but not yet developed for a proposed Engineered Roadway Soil (ERS). This study describes a systematic method where EPH model fits were developed based on material characterization tests, and then validated against physical tests with two different types of large flat plates. The accuracy of this model has been shown in nine different comparisons of plate velocity (impulse) or deformation to be well within 11.3%. This model is therefore deemed to be accurate enough and acceptable for usage of UBB simulations in the Army.

INTRODUCTION

Protection of US Army vehicles and soldiers against landmine and IED threats is an increasingly important concern in the area of defense research. Traditionally, military vehicles are designed and developed based on many component and full vehicle tests. During the development stage, the components and prototype vehicles cost much more than the same components and vehicles produced in mass production quantities. The live fire tests are complicated and very expensive to set up as well. Furthermore, it is a time consuming process to build prototype components and vehicles. Because the physics of crew kinematics, occupant injury mechanism, and vehicle behavior are very complicated during a mine blast and/or an IED explosion, many more physical tests than those that can be afforded are needed in order to make sure a military vehicle with super quality in survivability is designed and developed in the early design phase. Like many other industries, such as automotive and aerospace industries, computational modeling and simulation becomes a crucial process alternative to their traditional metal-cutting and testing process in order to gain more knowledge of the physical phenomena with lower costs and fast turnaround time.

The computational underbody blast (UBB) M&S has been used in military ground vehicle acquisition, design and development for several years and has helped engineers to develop vehicles with improved occupant survivability, and assisted PEO/PM to select appropriate technology in its acquisition even before live fire tests. The current UBB modeling and simulation processes and tools used in Department of Defense (DoD) agencies and its contract industry partners are relevant and effective, but have limitations. Back in 2010 summer, Secretary of Defense Memorandum required review of adequacy and availability of UBB modeling and simulation (M&S) tools and recognized the deficiencies. Monthly workshops were organized with subject matter experts (SME) across the DoD

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to include Army, Navy, Air Force, USMC, PEO/PMs, ATEC, DOTE, HPCMPO, DDRE and NGIC in order to access current capability of UBB M&S, to identify the gaps in the current UBB M&S, and to develop plans to close the gaps. This DDRE "Summer Study" identified top 10 gaps in the current underbody blast modeling and simulation. Three dedicated programs were initiated and funded to address these gaps. The Near-term Underbody Blast (NTUBB) Modeling and Simulation Enhancement program was initiated and lead by Analytics of TARDEC, and funded by ASA(ALT) to conduct deep-dive research works to close six gaps out of the top 10 identified. Characterization of geo material, and validation data generation of threat loading coupled with soil are two fundamental tasks of the NTUBB program. The research work described in this paper is a portion of the NTUBB program research efforts in closing those top 10 gaps identified in the UBB M&S.

In the underbody blast simulation, most blast load problems can be divided into four phases: detonation, propagation, interaction and target response [1]. In the detonation phase, the exploding source is detonated and quickly generates gases with high pressures and temperatures that propagate outwards by generating shock waves that interact with the surrounding medium. The propagation phase is where high intensity blast waves and ejecta propagate from the source towards the target. The interaction phase is where the airblast waves and soil ejecta interact with the target. The final phase is the response of the target due to the impulse of the dynamic loading environment.

LS-DYNA [2], a commercial software package, has been the workhorse tool used in TARDEC and other Army groups to perform UBB (Under Body Blast) modeling and simulation for several years [3-5]. Its Arbitrary Lagrangian-Eulerian (ALE) and multi-material Eulerian formulations make it possible to follow large flows of various materials without encountering numerical distortion problems often experienced in Lagrangian formulations. Also the Fluid-Structure Interaction (FSI) used in LS-DYNA is a penalty contact algorithm to treat the interaction behavior of blast waves/ejecta and the target structure.

The Elastic-Plastic Hydrodynamic (EPH) material model [2] of DS Topsoil *aka* brown clayey sand [6] has been used in TARDEC since 2012 for the UBB simulations. The Engineered Roadway Soil (ERS) had been newly proposed for survivability testing, but there was no known EPH model fit for this soil. To support this, an EPH model fit of ERS has been developed by TARDEC and Engineering Research Development Center (ERDC). It is noted that EPH is a material model built in LS-DYNA [2]. It uses the keyword *MAT_ELASTIC_PLASTIC_ HYDRO_SPALL. The purpose of this paper is to develop and validate the new EPH soil model for ERS.

BACKGROUND

The selection and specification of not only the actual soil, but also its emplacement condition in Survivability testing and evaluation of ground vehicles and occupants, plays a critical part of the force protection process in the Army acquisition process. The soil currently used in support of the majority of blast events is generically classified as average, dry loam (double screened/sifted top soil) and the test beds prepared per an interpretation of ITOP 2-2-617 [7] with respect to prescribed limits on bulk/wet density and moisture of the soil. This DS Topsoil has been characterized under Unified Soil Classification System (USCS) test results [8, 9] as either a Clayey Sand (SC-SM) or Sandy Clay (CL). This soil has been accurately characterized at the specimen level and validated for the impulse and deformation in larger plate tests [6]; specifically, an EPH soil model has been developed and currently in widespread use in the Army for Modeling and Simulation (M&S) of the DS Topsoil in underbody blast and other survivability applications.

There are some known issues with usage and emplacement of the DS Topsoil, the most prominent of which are listed here:

- Wide and consistent procurement of the soil at different geographic locations, in large quantities and per the prescribed ITOP specifications is questionable.
- Although limited testing of the soil has shown a fairly consistent gradation, it is not blended to a specification, and current process controls are not sufficient to guarantee the soil consistency.
- The allowable values on bulk/wet density and moisture of the soil per the ITOP are such that large variations in performance are possible if the full ranges of limits are exercised.
- The mid-range values of the soil emplacement conditions are looser than and have the potential to not be representative of some roadway conditions.
- The soil sometimes contains organic material such as: debris, roots, wood, scrap material, vegetation, refuse or soft and unsound particles that can produce inconsistent results.

To address these issues, a cross-agency team from the ERDC of US Army Core of Engineers, TARDEC, US Army Research Laboratory (ARL), ATEC, etc., worked under the auspices of the Occupant-Centric Platform Technology-Enabled Capability Demonstrator program (OCP-TECD) to develop a proposal for selection criteria of a new soil and accompanying emplacement condition for survivability testing. Working off a preliminary draft by ERDC [10], the team developed specifications for an ERS, the salient features of which are as follows:

- As the name implies, the soil is constructed/produced from an engineered specification, therefore it can be

produced widely in large quantities at different geographic locations from locally available material.

- Requirements now include specifications on upper and lower bounding grain sizes, acceptance of only SC, SM, or SC-SM soils per USCS Classification, with some additional limits on some grain sizes not listed here.
- Free of organic material.
- Emplacement to achieve the compaction level associated with a roadbed (i.e., greater than 95 percent standard Proctor curve maximum dry density). The ERDC recommendation of moisture content is ±1.5 percent of the above optimum value for roadbed construction.

VALIDATION APPROACH

The approach employed to validate the new EPH geo-material model is to use the experimental data from the two series of simplified physical tests. The first series of simplified physical tests are conducted by using a rigid plate standing above a buried charge inside the studied soil as shown in Fig. 1. The steel plate is very thick and its deformation during an underbody blast load is negligible. No instrumentation is equipped with the plate. The objective of this series of tests is to validate the soil loading to the plate by using the plate kinematic movement, such as impulse and velocity. The plate velocity and maximum flight height are recorded by using high speed camera. The second series of simplified physical tests use a thinner stainless steel plate at the very bottom with concentrated mass on its circumferential edge as shown in Fib. 2. The deformation measurements from this series of tests are used to validate the blast/soil loading caused structural deformation. During physical tests, two different charge sizes are used in each series of tests.

Two computational models of the test setup have been developed to validate the newly-developed EPH model of the ERS. In each of the two FEA models, there are four major components: plate structure, charge, Engineered Roadway soil, and air. Fig. 1 shows the first model, where the four parts are respectively in blue, brown, red, and yellow colors. After the charge is detonated, the airblast along with the soil ejecta impact the unconstrained rigid steel plate. The plate is therefore impacted to fly vertically. In the blast test, the maximum height of the plate travel is obtained by analyzing the high-speed video. The maximum velocity of the plate can then be calculated from the kinematic equations for projectile motion. Also, the product of the plate mass and the maximum velocity equals the maximum impulse imparted to the plate.

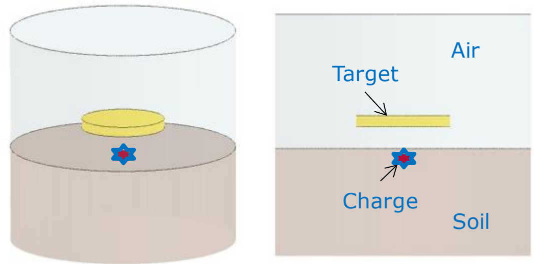

Figure 1: Rigid plate blast model

In the simulation model, the time history of the rigid plate vertical velocity is extracted and the maximum velocity is determined from the velocity history. The comparisons of the maximum velocity between the simulations and tests are then used to determine the accuracy of the EPH model.

In the second model, the plate used is thinner and flexible, in a holding fixture. Fig. 2 shows this model, where the circular flexible plate is clamped at the outer edge by the holding fixture. In the blast test, the deformations at the plate center and the mid-point, *i.e.*, halfway between the plate center and outer edge, are measured after the blast.

The time histories of the flexible plate's deformations are extracted from the simulation results. The deformation at the end of the simulation, 15 milliseconds (ms), is treated as the permanent deformation of the plate. The comparisons of the deformations between the simulations and tests are further used to determine the accuracy of the EPH model.

FINITE ELEMENT MODELS

In this section, the LS-DYNA finite element models developed to simulate simplified plate under blast loading are described. The details of these two models are described in the following sections: Part Dimensions, Element Type and Size, Material Properties and Other Important Parameters.

Part Dimensions

Two circular flat plates are modeled separately as shown in Figs. 1 and 2. The first one, referenced as rigid plate, has the dimensions of 0.914 m in radius and 0.203 m in thickness, which is made of mild steel and has a mass of 4209 kg. The second model, referenced as flexible plate, consists of two parts: a circular flat plate and concentrated mass ring mounted on its circumferential edge . The plate is made of 304 stainless steel, and has the dimensions of 0.914 m in radius and 0.0381 m in thickness. The RHA steel ring fixture has, respectively, 0.610 and 0.914 m of inner and outer radii, and 0.165 m in thickness. The total mass for the second setup is 3586 kg.

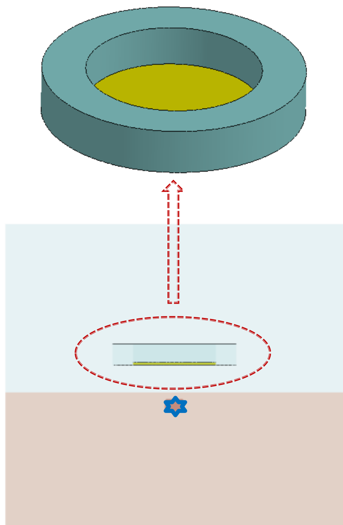

Figure 2: Flexible plate blast model

Two different charge masses are used in the buried threat simulations: Charge-Low and Charge-High. Each charge's shape is cylindrical with the centerline along the vertical direction.

The radius and height of the Eulerian soil domain sizes are, respectively, defined as 2.5m and 2.0m. Also, the radius and height of the Eulerian domain size for the air are all defined as 2.5m. These sizes are deemed to be reasonable for capturing the maximum velocity of the plate and reducing the analysis time. Too large a domain size will unnecessarily increase the simulation time.

Element Type and Mesh Size

All the elements used in this model are 3d 8-node solids. The mesh size, *i.e.*, the length of each side in the solids, is critical to the analysis of any finite element problem. A mesh size of 20mm is used herein for all the parts. It is deemed to be a good compromise between solution accuracy and analysis time for this type of UBB simulation problems [3].

Material Properties

LS-DYNA uses both a Constitutive Model (CM) and an Equation of State (EOS) to describe some materials [2]. The former defines the stress-strain relationship and failure criteria, while the EOS relates the pressure to the specific volume, and temperature of a material at a physical state. The material and EOS for air are specified, respectively, by LS-DYNA cards *MAT_NULL and EOS_LINEAR_POLYNOMIAL [2] in this model [3, 4]. The charge properties are modeled by *MAT_HIGH_EXPLOSIVE_BURN and *EOS_JWL [2]. This modeling approach is commonly employed in blast analysis [3, 4, 6].

The keyword *MAT_RIGID [2] is used to model the rigid plate to save simulation time. Also, no EOS card is required for such a material type. For the flexible plate case, the holding fixture is also considered rigid due to the large thickness. The flexible flat plate is modeled by the keyword *MAT_PIECEWISE_LINEAR_PLASTICITY [2].

For the soil, the same keywords are used as in [6]. That is, *MAT_ELASTIC_PLASTIC_HYDRO_SPALL and *EOS_TABULATED_COMPACTION. This will be explained in details later.

Other Important Parameters

Two other important parameters in the models are Standoff (SO), and Depth Of Burial (DOB). The SO is the distance between the bottom of the plate and the top of soil surface, while DOB is the distance between the top of the charge and the top of soil surface.

LS-DYNA EPH MODEL

LS-DYNA has more than 100 different built-in materials to cover various solids and fluids. The EPH material model, with the keyword *MAT_ELASTIC_PLASTIC_HYDRO_SPALL, is the 10th material (MAT010) in LS-DYNA library. The key properties in *MAT_ELASTIC_PLASTIC_HYDRO_SPALL are density (*r0*), shear modulus (*g*), yield stress (*sigy*), plastic hardening modulus (*eh*) and cut-off pressure (*pc*).

A tabular EOS with LS-DYNA keyword *EOS_TABULATED_COMPACTION is used herein to define the loading and unloading Pressure-Volume (P-V) strain response. The P-V response also defines the bulk modulus (*K*) of the material. LS-DYNA performs a linear interpolation between the points in the lookup table resulting in a piecewise linear functional approximation of the pressure-volume relation. Ref. [6] shows how to obtain the material properties, and also how to convert a P-V response into the format used by *EOS_TABULATED_COMPACTION, which is represented by ten points from (*ev1, c1*) to (*ev10, c10*) for DS Topsoil. The notations *evi* and *ci* are the volume strain and pressure, respectively, for the *i-th* point.

EPH MODEL FOR ERS

To characterize soil material, several laboratory tests are needed. These include hydrostatic compression, TriaXial Compression (TXC) and UniaXial (UX) strain tests. Ref. [11] explains the details of each test process and resulting output. In the past, these test procedures have been used to develop Hybrid-Elastic Plastic (HEP) model fits for several soils including ATC test bed soil [11], and also to develop EPH model fits for the brown clayey sand [6]. The ERDC

HEP geo-material model has proven to be an effective model for a wide variety of soils and other geo-materials in Lagrangian finite element simulations of blast and penetration. The objective of this study however is to use the same laboratory data to create material models for the EPH formulation.

To construct the EPH model for ERS, the same laboratory test results had to be obtained first for this soil. These results, tested by ERDC [12], are shown in Figs. 3 through 5 for UX P-V response, UX stress path and failure surface, respectively. It should be noted that the tested soil had 17.6% AFV (Air Filled Void). AFV can be calculated by knowing the grain density, dry density, and water content of the tested soil [6]. After obtaining the test data of the soil, a similar procedure [6, 11] was applied to create the EPH model for ERS with 17.6% AFV.

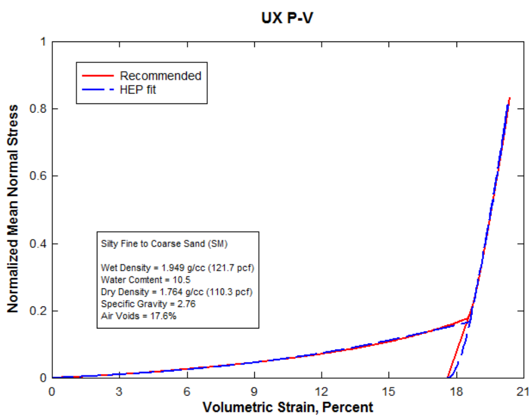

Figure 3: UX P-V response of the soil test

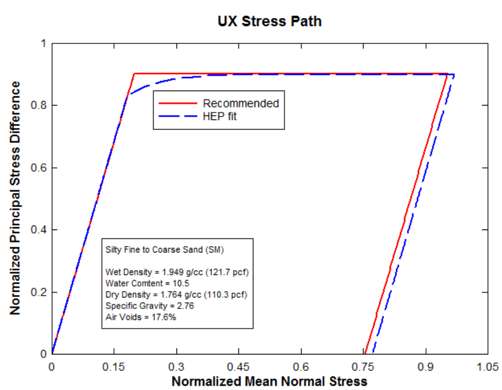

Figure 4: UX stress path of the soil test

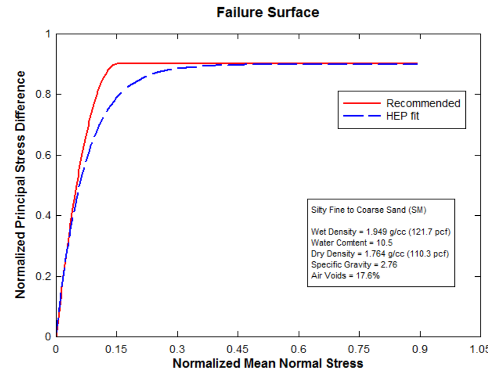

Figure 5: Failure surface of the soil test

As mentioned earlier, the simulation results are used to compare with the test results to validate this EPH model of the ERS. Also, in each test bed, the actual AFV may not be the same as the lab-tested value, *i.e.*, 17.6%. Therefore, a different EPH model was created for the actual measured AFV value in the tests, to ensure the right basis for comparisons. The modifications for different AFVs are mainly to soil density and EOS per previously published research [6]. As an example, EOS curves with three different AFVs: 11.5%, 13.6% and 17.6% are plotted together in Fig. 6. It can be seen that for the same volumetric strain, the soil with the lower AFV has the higher pressure. This also means that it will generate higher impulse for a lower AFV soil.

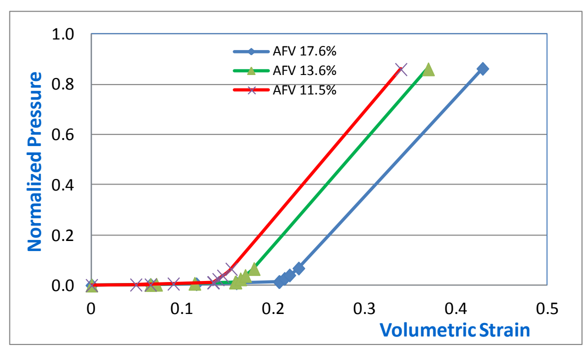

Figure 6: EOS curves with three different AFVs

VALIDATION CASES

As mentioned, two cases have been created to compare the simulation and test results for validating the accuracy of the EPH model fit of ERS. In each case, the values for SO and DOB are set to 0.406 and 0.1 m, respectively, as in the tests.

Case 1: Rigid Plate

Five blast tests of flat plates were performed for case 1 [13]. Three of these were detonated with Charge-Low, and the other two were detonated with Charge-High. The actual AFV in each test bed was calculated as follows. First, the dry density and water content are measured at 12 different locations in the test bed, then the AFV is calculated using the material's grain density, averaged dry density and water content. The resulting AFVs were respectively 13.4%, 15.0%, 14.2%, 15.3% and 14.9% for the five test beds.

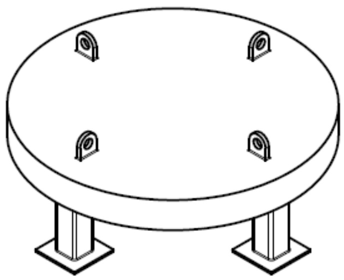

Figure 7: Rigid plate test setup

The blast test set-up is shown in Fig. 7. The maximum height of the rigid plate travel (also called jump height) is obtained from the test data, and the maximum velocity of the rigid plate is then calculated. The three "normalized" maximum velocities obtained from the tests [13] are listed under "Vtest" in Table 1 as: 1.000, 0.915 and 0.937 for the Charge-Low cases. All test and simulation velocities shown in Table 1 were normalized by the largest velocity value observed in the three tests. The same results for the Charge-High cases are respectively shown in Table 2 as 1.000 and 0.928.

Table 1: Rigid plate velocity results for Charge-Low

	Test A	Test B	Test C
AFV	13.4%	15.0%	14.2%
Vsim	0.949	0.880	0.911
Vtest	1.000	0.915	0.937
Diff.	5.1%	3.8%	2.7%

For comparing with the five blast tests, five EPH models of ERS due to different AFVs were built. The five resulting normalized maximum velocities solved by LS-DYNA, labeled as "Vsim" are also listed in Tables 1 and 2. It can be seen from Table 1 that the differences between the simulation and test are, respectively, 5.1%, 3.8% and 2.7% for the Charge-Low cases. The differences for the Charge-High cases as shown in Table 2 are, respectively, 11.3% and 0.4%. The comparisons are also plotted in Figs. 8 and 9 in the form of maximum velocity vs. AFV. A screen shot of the simulation at 6ms from one of the five analyses is also shown in Fig. 10.

Table 2: Rigid plate velocity results for Charge-High

	Test D	Test E
AFV	15.3%	14.9%
Vsim	0.887	0.925
Vtest	1.000	0.928
Diff.	11.3%	0.4%

Case 2: Flexible Plate

In this case, two blast tests of flat plate and its holding fixture were performed. They were detonated with Charge-Low. The actual AFVs in the test beds were calculated, respectively, as 12.2% and 12.3%. Fig. 11 shows the blast test set-up. After the blast tests, the deformations at the top surface of the plate center and the mid-point are measured. The four normalized deformation results [14-15] are listed under "Dtest" in Table 3 as: 0.923 and 0.738 for the center and mid-point, respectively, for test F, and as: 0.992 and 0.790 for test G.

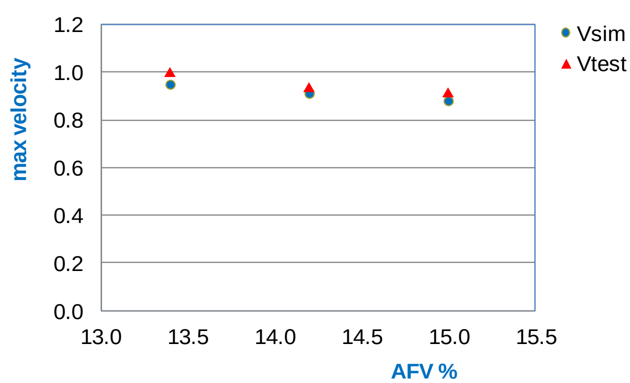

Figure 8: Rigid plate results for Charge-Low

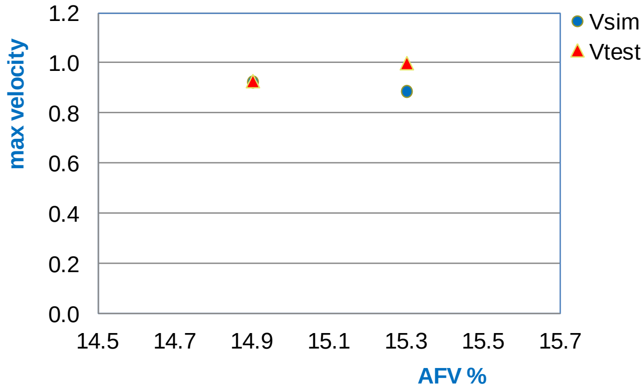

Figure 9: Rigid plate results for Charge-High

For comparing with the blast tests, two EPH models of ERS with 12.2% and 12.3% AFV, respectively, were built. The deformation at the end of the simulation, 15ms, is treated as the permanent deformation of the plate. Such deformations at the plate center and mid-point can be extracted by LS-DYNA Pre- & Post-processor (LSPP). Fig. 12 displays the simulated permanent deformations of the plate. The deformed overall shape matches very well with the test. The resulting four normalized deformations, labeled as "Dsim" are also listed in Table 3 as: 1.000, 0.778, 1.000 and 0.778, respectively. All test and simulation deformations shown in the table were normalized by the largest deformation value in the simulations. It can be seen from Table 3 that the differences between the simulation and test are, respectively, 8.3%, 5.5%, 0.8% and 1.5%. A screen shot of the animation at 10ms is also shown in Fig. 13.

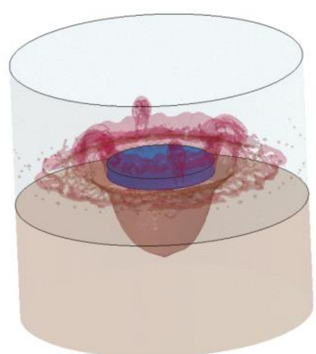

Figure 10: Rigid plate blast simulation

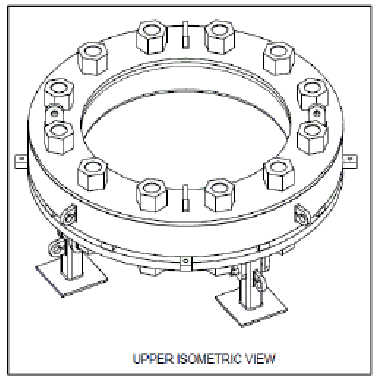

Figure 11: Flexible plate test setup

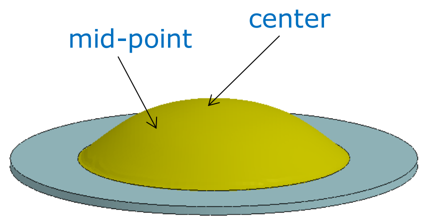

Figure 12: Flexible plate simulation results

Figure 13: Flexible plate blast simulation

Table 3: Flexible plate deformation results

	Test F		Test G	
Location	center	mid-point	center	mid-point
AFV	12.2%	12.2%	12.3%	12.3%
Dsim	1.000	0.778	1.000	0.778
Dtest	0.923	0.738	0.992	0.790
Diff.	8.3%	5.5%	0.8%	1.5%

DISCUSSION AND CONCLUSIONS

The development of LS-DYNA EPH material model for ERS has been described in this study. The accuracy of the model is demonstrated by comparing the simulated velocity/deformation results with the test measurements. These comparisons show:

(1) The three velocity comparisons for Charge-Low are all within 5.1%
(2) The two velocity comparisons for Charge-High are 0.4% and 11.3%, respectively
(3) The four deformation comparisons for Charge-Low are all within 8.3%.

The new EPH model is therefore deemed to be accurate enough and acceptable for usage of UBB computational M&S in the Army. Also the new EPH soil material model has been applied to several vehicle programs in TARDEC.

It is expected that the ERS and emplacement conditions described in this study will lead to more consistent results with lesser test-to-test variation when compared to the DS Topsoil, mainly due to tighter limits in bulk/wet density and moisture of the soil, ensured by tighter test bed preparation procedures. Being more representative of theater-like soil conditions in both composition and compaction, it is felt that the new soil is a more realistic predictor of ground vehicle design performance, leading to enhanced soldier survivability. It is imperative that M&S models keep abreast with modifications to testing procedures, always maintaining appropriate physics-based math models for different soils. M&S is an important risk-management tool to develop vehicle systems and blast mitigation designs that keep the soldiers safe and uninjured in underbody blasts. Since full-vehicle physical testing is both expensive and time-consuming, M&S is being used to explore the design to a wider threat space, thus minimizing risk.

DISCLAIMER

Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Dept. of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoD, and shall not be used for advertising or product endorsement purposes.

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ACRONYMS

AFV	Air Filled Void
ALE	Arbitrary Lagrangian Eulerian
ARL	Army Research Labs
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics & Technology
ATEC	Army Test and Evaluation Center
ATC	Army Test Center
CL	Sandy Clay
CM	Constitutive Model
DDRE	Director of Defense Research and Engineering
DOB	Depth Of Burial
DoD	Department of Defense
DOTE	Directorate of Test and Evaluation
DS	Double-Sifted
EOS	Equation of State
EPH	Elastic-Plastic Hydrodynamic
ERDC	Engineering Research Development Center
ERS	Engineered Roadway (or Roadbed) Soil
FSI	Fluid Structure Interaction
HEP	Hybrid Elastic Plastic
HPCMPO	High Performance Computer Modernization Program Office
IED	Improvised Explosive Device
ITOP	International Test Operations Procedure
JWL	Jones-Wilkins-Lee (Eq. of state for explosives)
LSPP	LS-DYNA Pre- & Post-processor
M&S	Modeling & Simulation
NGIC	National Ground Intelligence Center

NTUBB	Near-Term Under Body Blast modeling and simulation enhancement program
OCP_TECD	Occupant-Centric Platform Technology-Enabled Capability Demonstrator
P-V	Pressure-Volume strain
PEO	Program Executive Office
PM	Program Manager
SC-SM	Clayey Sand
SME	Subject Matter Expert
SO	Standoff
TARDEC	Tank Automotive Research, Development and Engineering Center
TXC	TriaXial
UBB	Under-Body Blast
USCS	Unified Soil Classification System
USMC	U.S. Marine Corps
UX	UniaXial

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